Selection of decoupling points in supply chains using a knowledge-based approach

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Abstract: As consumer affluence and desire for customized products and services at affordable prices and shorter lead times continue to accelerate, supply chain operators are facing increasing challenges of becoming both physically efficient (to enable the delivery of low cost) and flexible (to enable market-responsiveness). In order to meet these challenges, organizations are devising supply chain operation strategies that enable them to gain the benefits of physical efficiency of mass production and the customer focus of mass customization. A key to gaining these benefits lies in the selection of appropriate decoupling points in the supply chain. Decoupling points lie on the push–pull boundary. The selection of decoupling points requires knowledge from a range of different experts. The research reported in this paper used knowledge-based techniques to bring together knowledge from the viewpoints of different experts in the selection of decoupling points in supply chains. A knowledge model in the form of a network of production rules is presented. Results derived from applying the knowledge model to the case studies show similar trends to published literature.

Keywords: customer order decoupling point, lean-agile supply chain, knowledge-based decision support tool, mass customization, push–pull boundary.

1 INTRODUCTION

Supply chains have existed ever since people started trading. In recent times businesses are paying increasing attention to supply chain operation and management, with a view to improving their performance and competitive advantage. Businesses are facing increasing competition and challenges to get closer to their customers, reduce time to market, reduce costs, increase variety, improve quality, eliminate inventory, be right first time, add innovations, improve reliability, and increase flexibility to their products and services (i.e. react nimbly to changing markets). In addition, as asserted by Bowersox *et al.* [**1**], the world of commerce has been irrevocably impacted by computerization, the Internet, and a range of inexpensive information transmission capabilities. These information and digital technologies have paved the way for B2B (business-to-business) and B2C (business-to-consumer) commerce. To meet these emerging business challenges, supply chains are being redefined and restructured. Businesses are increasingly focusing on their core activities and outsourcing non-core activities to the suppliers. Operations not just for the efficiency of the individual firms in the supply chain but also for efficiency and effectiveness of the whole supply chain are increasingly becoming strategic postures. To achieve this, supply chain partners must collaborate with each other, for example, by sharing risk and revenue, providing visibility throughout the supply chain, and appropriate supply chain operations strategies.

Two widely used supply chain operations strategies are the so called ‘push–pull’ and ‘lean-agile’ systems. A common feature of these two systems is the need to identify decoupling points that lie on and define the boundary between forecast-driven and demand-driven sections of the chain. A wide range of factors influence this decision and so requires input from a range of viewpoints and experts.

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This paper reports research that demonstrates how knowledge-based technology might be used to bring together view points of multiple domain experts to support decisions related to the positioning of decoupling points in supply chains. Key strategies for supply chain operation are outlined in section 2. Problems relating to and existing approaches for, the selection of supply chain decoupling points are discussed in section 3. Section 3 also introduces engineering and manufacturing issues that influence the positioning of decoupling points in supply chains. A knowledge model that encapsulates some of these issues in the form of domain knowledge is presented in section 4. A case study is used to demonstrate how the knowledge model can be used to support decisions related to the positioning of supply chain decoupling points. Key results are presented in section 6 and, in section 7, validated against results of earlier research reported in the literature.

2 STRATEGIES FOR SUPPLY CHAIN OPERATION

Push–pull and lean–agile are two widely used supply chain operation strategies. In the push strategy, long-term demand forecasts are used to plan supply chain operations schedules. Goods are 'pushed' from one stage to the next, downstream through the supply chain until the finished or semi-finished products reach the warehouse where they are kept as stock-keeping-units. A key advantage of the push strategy is its physical efficiency; a key disadvantage is its disconnection from the demands of the marketplace or customer. On the other hand, in the pull strategy, supply chain operations are driven by actual customer demand rather than forecasts. Customer demand pulls goods through the supply chain without the need for a predetermined operations schedule. This demand pull is transmitted from the end customer to the end supplier through intermediate suppliers. An advantage of an ideal pull strategy is that no inventory is held and all production is driven by customer demand; in reality, inventory is held, usually by companies upstream in the supply chain, to act as a buffer for fluctuations in customer demand. The potential benefits of both the push and pull strategies have led to the emergence of a hybrid push–pull strategy for supply chain operation where some stages of the supply chain, typically the initial (upstream) stages, are operated in a push-based manner whilst the remaining stages, typically the later (downstream) stages, are operated using a pull-based strategy. The part of the supply chain following the push strategy provides physical efficiency while the part of the supply chain following the pull strategy provides customer responsiveness and flexibility. The point in the supply chain where the strategic mode of operation is shifted from push to pull is referred to as the decoupling point or the push–pull boundary[1] [**2**]. Safety stocks are often kept at the push–pull boundary to act as a buffer against fluctuating and uncertain customer demands.

The lean paradigm emerged from the Toyota Production Systems and the agile paradigm was introduced by the Iacocca Institute, Lehigh University, USA. The so-called 'lean–agile' approach combines the two approaches. In the lean paradigm the goal is to maximize utilization of resources; the major advantages of the lean philosophy are the elimination of waste and thereby increase in physical efficiency. A major limitation of lean principles, however, is that its success heavily depends upon planning based on demand forecasts. There is a great deal of confusion over the term 'agile'. Nagel *et al.* [**3**] and Kidd [**4**] provide working definitions to the term 'agility'. For the research reported in this paper 'agility' means being fast and flexible, customer responsive and customer specific, change-embracing, and able to use market knowledge to exploit profitable opportunities and growth in a volatile market place. A major advantage with the agile philosophy is that planning based on future demand forecasts is not essential for its success. It advocates becoming 'fast and flexible' as well as 'totally customer focused' even at the expense of other kinds of slack or waste, such as, keeping a safety stock or experiencing a higher manufacturing cost. For this reason agile principles are more appropriate where uncertainty and variability are high and therefore, decisions are made only in response to realized demand. The lean–agile approach combines the best from both of these paradigms: bringing together the physical efficiencies of the lean philosophy with the flexibility and customer responsiveness of the agile philosophy. Towill and Christopher [**5**], Naylor *et al.* [**6**], and Mason-Jones *et al.* [**7**] discussed this combined lean–agile philosophy as an effective strategy for supply chain operations. In the lean–agile approach, the upstream of the supply chain embraces the lean philosophy of operations to bring physical efficiency whilst the downstream of the supply chain follows the agile philosophy and is therefore able to better respond to changing requirements and fluctuating demands of end customers. The decoupling point, as in push–pull systems, is the point in the supply chain that marks the place where the supply chain operation strategy shifts from 'lean' to 'agile'. As stated by Naylor *et al.* [**6**]

[1] *This term was extensively used by David Simchi-Levi of the MIT Forum for Supply Chain Innovation & Engineering Systems Division.*

Downstream from the decoupling point all products are pulled by the end-user, that is, they are market driven. Upstream from the decoupling point the supply chain is initially forecast driven. However, with the advent of Kanban driven supply, this has become more than simply a push system.

In other words, whilst for the downstream supply chain processes of the decoupling point it is pull execution, for the upstream supply chain processes it is push plan and pull execution [**6**].

The push–pull strategy can be mapped onto the lean–agile strategy for supply chain operations and parallels can be drawn among equivalent concepts. In a strict literal sense, the terms ‘push–pull’ and ‘lean–agile’ paradigms of supply chain operations are not the same. However, as the ‘lean’ part of a ‘lean–agile’ supply chain is forecast driven as is the ‘push’ part of a ‘push–pull’ supply chain, for the purpose of decoupling point selection they can be regarded as equivalent. Similarly, the ‘agile’ part of a ‘lean–agile’ supply chain and the ‘pull’ part of a ‘push–pull’ supply chain can be considered equivalent as both of them are demand driven and operated in pull mode.

A key strategic decision for supply chain planners lies in deciding where to position the decoupling point in a given supply chain. The goal of the research reported in this paper was to explore the potential of using emerging knowledge representation technologies to inform decisions related to the positioning of decoupling points in supply chains. Information from a range of viewpoints (represented by multiple domain experts) and factors that influence decoupling point selection is captured. An experimental software prototype was built and used to investigate the effects of product structure, product variety, component commonality, differentiation and postponement strategies, and process flexibility on the positioning of decoupling points in example supply chains.

3 DECOUPLING POINT SELECTION

3.1 Real-world problem scenario

The Cannondale Bicycle Company is used as a case study in this paper (Data for this case study came from,

(a) the reports and information publicly available in the URL www.cannondale.com [**8**];
(b) [**9**] and [**10**]).

The example scenario given in Fig. 1 was used to illustrate the practical problems that were addressed through the research.

It can be seen from the scenario, and also as pointed out by Fisher [**11**] that ‘innovative’ and ‘functional’ products are at two opposite extremes of a classification spectrum of products based on utility, nature of demand, and perceived value. Mason-Jones *et al.* [**7**] asserted that for innovative products ‘service level’ is the market winner metric whilst quality, price and lead time are market qualifiers. On the other hand, for functional products the market winner metric is ‘price’ whilst market qualifiers are quality, lead time, and service level. Mason-Jones *et al.* [**7**] argued that supply chains must excel at the market winner metrics and be highly competitive at market qualifier metrics. Market qualifier metrics

> Cannondale Bicycle Co. owns two brands of mountain bike: Jekyll and F-Series.
>
> Products of the ‘Jekyll’ brand are trendy, highly customized, and innovative in design and make; they are relatively expensive and have a wide range of variety delivered through combinations of user selected options. Jekyll branded products have short product and part life-cycles which means that new products are frequently introduced to the market. The lead time for bringing new Jekyll products to market is short and their obsolescence rate is high because fashions in the marketplace change frequently. It is difficult to forecast demand accurately for products of the Jekyll brand because of highly fluctuating demand patterns. Some product variants tend to have high stock-out rates during peak seasons, resulting in lost opportunities in sales; however, at other times, variants have to be marked down at the end of season to prevent financial losses as those variants become out-dated. The brand owner has a high profit margin from the products of this brand. For repairs or replacements, most of the parts are difficult to find from independent dealers and retailers. Because of its highly integral product structure, some parts are difficult to replace.
>
> On the other hand, products from the ‘F-Series’ brand are less customized and more functional, not very innovative in their design and use mainly standardized parts in their construction. F-Series products have a highly modular product structure with many interchangeable parts. The F-Series brand is relatively inexpensive and has a narrow variety range but significantly longer product and part life-cycles than Jekyll products. Every year only a few new products or parts are introduced and, as a result, they have a relatively low obsolescence rate. Demand forecasts for products of the F-Series brand can be based on historic demand data and tend to be reliable since demand patterns are relatively smooth. Stock-out situations for any particular variant are not common but the brand owner has a low profit margin from F-Series products. For repairs and replacements, most parts are available off-the-shelf from independent dealers and retailers.

Fig. 1 An example scenario

set the minimum standards to enter a marketplace. For these reasons, it can be concluded that the priorities of supply chain operation for innovative products differ from those for functional products.

3.2 Supply chain operation

Fisher [**11**] asserts that a supply chain performs two distinct types of function: a physical function and a market mediation function. The physical function of a supply chain is readily apparent and includes converting raw materials into parts, components, and eventually finished goods, and transporting them from one point in the supply chain to the next. The equally important but less visible market mediation function ensures that the variety of products and services reaching the marketplace matches consumers' expectations as fully as possible. Each of these two supply chain functions incurs costs. To address these 'physical' and 'market mediation' functions and costs incurred by them, an effective supply chain operation strategy is needed. An effective supply chain should be both 'efficient' in terms of 'physical' functions and 'responsive' in terms of 'market mediation' functions. As explained in section 2, push–pull or lean–agile strategies can be used as supply chain operation strategies to deliver physical efficiency as well as market responsiveness. Such supply chain operation strategies have to be devised for diverse kinds of product ranging from the highly innovative to the highly functional (according to Fisher's, classification scheme of products [**11**]). A key decision for supply chain managers lies in where to best position decoupling points. This is an important question because the decoupling point coincides with the customization point for a product: where product differentiation is started or until which product differentiation is postponed.

Although a large number of papers have been published in literature on hybrid push–pull or lean–agile strategies of supply chain operation, only a very limited number of them have focussed on systematic approaches to the selection of decoupling points in supply chains. However, there is a growing interest in the industrial community to make better informed decisions related to the appropriate location of decoupling points in supply chains. The DTI's Global Watch Mission Report [**12**] reports a number of industrial cases where positioning of decoupling points in supply chains were considered to be major issues.

Simchi-Levi and Simchi-Levi [**13**] provide a framework to match supply chain strategies with products and industries. The framework developed by Simchi-Levi and Simchi-Levi [**14**] characterizes the levels of push and pull required for different products. To locate the push–pull boundary for different products (requiring different levels of push and pull), a supply chain time line is considered that represents the time that elapses between procurement of raw material (beginning of the time line) and the delivery of an order to the customer (end of the time line). The push–pull boundary is selected somewhere along the time line; the push–pull boundary for different industries and products is shown in Fig. 2. Typically, the nearer the push–pull boundary is to the beginning of the supply chain time line, the higher the inventory cost per unit but the shorter the delivery lead time to the customer.

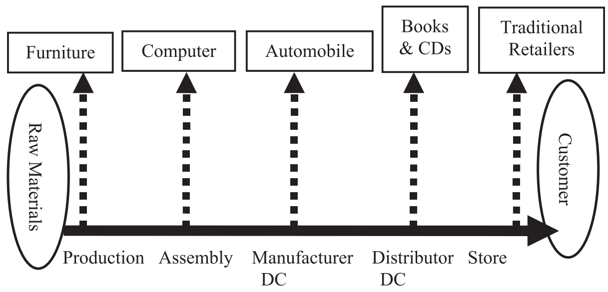

Fig. 2 Typical locations for the push–pull boundary in sector-specific supply chains (from Simchi-Levi and Simchi-Levi [**14**])

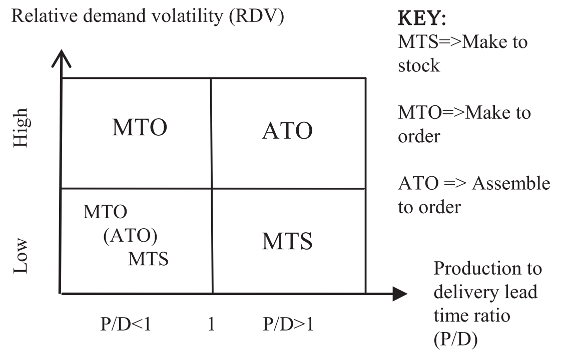

Fig. 3 A model for choosing the right product delivery strategy (from Olhager, [**15**])

Deciding upon the positioning of the push–pull boundary requires the making of trade-offs between conflicting requirements, for example, balancing cost to the customer with delivery lead time.

Olhager [**15**] identifies the production to delivery lead time ratio (P/D ratio) and the relative demand volatility (RDV) as two major factors affecting strategic positioning of the order penetration point (also known as customer order decoupling point). RDV is the standard deviation of the demand relative to the average demand. Both these factors can range from low to high, leading to four combinations with different properties pertaining to the choice of product delivery strategy, as shown in Fig. 3.

It is widely recognized that supply chains show characteristics of complex systems and, therefore, have emergent properties. According to Siemieniuch and Sinclair [**16**], a key factor in supply chain systems known to cause complex behaviours lies in the range of people and roles involved in a supply chain's operation. These people are often referred to as 'agents'. In a typical supply network there are many different kinds of agent, each with its own goals that both interact with each other and have autonomy in how they behave. Two sources of differences in the goals of individual agents, which directly influence their behaviour, are the strategic intents of the organizations to which they belong and the stage of the supply chain process within which they operate. In this research, the steps of supply chain operations processes considered were engineering and design, purchasing and procurement, manufacturing, assembly, storage-distribution-logistics, and retail sales and marketing. Parallel communication between agents often occurs and both the agents and the supply chain environment evolve over time: partly as a result of agents' actions and partly because of external factors such as, in salad vegetable chains, the weather in both the growers' and consumers' environments.

These stages of a supply chain operation are realized by different organizations involved in the supply chain. The Supply Chain Council[2], in its Supply Chain Operation Reference model (SCOR), asserts that each organization within a supply chain performs four high-level supply chain functions: planning, sourcing, making, and delivery.

3.3 Considerations in decoupling point selection

Current practice in the selection of decoupling points in supply chains primarily depends on the personal judgement of practitioners. Ramachandran *et al.* [**17**, **18**] identified three criteria for decoupling point selection in production lines of a manufacturing firm. However, their approach was particularly meant for decoupling point selection in the production lines of manufacturing firms and no reference was made to decoupling point selection in external supply chains. In external supply chains, a number of factors have been identified as influencing supply chain performance and the appropriate positioning of decoupling points. This paper focuses on the following factors: product structure, product variety, product differentiation and product postponement, component and part commonality, and component and part standardization. Significant overlaps can be found among these factors.

[2]*See Supply Chain Operations Reference-model 8.0 by Supply Chain Council (www.supply-chain.org) for more details.*

3.3.1 Product structure

The concept of product structure has been established by a number of commentators using a wide variety of definitions. The research reported in this paper adopted the definition provided by Ulrich and Eppinger [**19**] and defines a product structure (also sometimes called a product architecture[3]) as the scheme by which functional elements of a product are allocated to its physical elements and the ways these elements interact.

Product structure influences the ease with which a product can be changed. For the purposes of the research reported in this paper, two kinds of product change were considered: change to a particular artefact over its life cycle (i.e. design changes and replacement of parts) and change to a product line or model across successive generations. With the latter type of change, product ranges can be extended whereas the former is typically achieved through the use of versioning. Product structure determines which functional elements of the product will be influenced by a change to a particular physical element and which physical elements must be changed to achieve a desired change to a functional element of a product [**20**]. At one extreme, a modular product structure allows each functional element of the product to be changed independently by changing only the corresponding physical element; at the other, a fully integral product structure requires change to every component to effect change in any single functional element [**20**]. For this reason, a product structure can be used as a guide in establishing the ease with which a firm can implement product changes. This, in turn, contributes significantly to the ease and flexibility with which an existing product in the market can be quickly customized or successive new product generations can be evolved and introduced, for example, in response to changing market requirements. The issue of market responsiveness significantly influences the selection of decoupling point in a supply chain.

A number of authors have noted that product structure is often mirrored in the supply chain structure that is used to deliver products to market [**21**]. For this reason, it can explicitly or implicitly influence supply chain performance in a number of ways. The decoupling point of a product in a supply chain is selected with the aim to optimize supply chain performance (i.e. to optimize physical efficiency and market responsiveness). As the decoupling point is selected for optimal supply chain performance, its selection is heavily influenced by product structure (in particular degrees of modularity in product structure).

[3]*This term was used by Ulrich and Eppinger [**19**] and Ulrich [**20**].*

With modular product structures, the one-to-one correspondence between functional elements and physical elements of a product allows variety to be created by customizing desired functional elements and thereby restricting requirements for customizations to only a few physical elements. For these reasons, a high degree of modularity in product structure allows variety to be created at the final assembly, usually the last stage of the manufacturing process [**20**]. Some firms even delay a part of their final assembly process until the product has moved through the distribution system and is ready to be shipped to the end customer. These characteristics of the highly modular products create opportunities to delay their customization until the very last stages of the supply chain. The knowledge model developed in this research (that will be shown as Fig. 5) illustrates the interactions between knowledge domains and captures knowledge related to product structure in the engineering and design, materials and parts procurement, manufacturing, assembly, and storage–distribution–logistics knowledge domains.

3.3.2 Product variety

Over the years, product variety has emerged as a key issue of market competition. Ulrich and Eppinger [**19**] referred to product variety as the diverse range of product models a firm can produce within a particular time period in response to market demand. Whilst mentioning product variety, it is important to mention the 'dimension' in which variety is being delivered. Variety dimensions may be stated in terms of a set of functional elements implemented by the product or in terms of the specific performance characteristics of the product relative to a particular functional element. High variety can be produced by any manufacturing system at a certain cost, but the key issue is to produce high variety economically. The ability of a firm to economically deliver variety can be attributed to a number of factors, including but not limited to, manufacturing and assembly flexibility, product structure, and raw-materials and parts procurement flexibility [**20**].

Manufacturing flexibility is often attributed to flexibility of the process equipment, manufacturing costs as well as flexibility of assembly systems [**20**]. Another important factor worth considering regarding manufacturing flexibility is lot size; the larger the lot size, the higher the inventory cost. However, inventory costs and set-up costs can be traded off against each other, e.g. smaller lot sizes can drive down inventory costs but increases set-up costs.

Much of a firm's ability to deliver variety resides within the product structure. Relationships between product variety and product structure have been extensively researched. According to Ulrich [**20**], with a modular product structure product variety can be achieved economically with or without flexible process equipment, while for an integral product structure, economic production of high variety requires flexible process equipment. He asserts that the strategy for delivering variety in a product is heavily dependent on both the degree of modularity and the kind of modularity being used. He identifies a number of different kinds of modularity, for example, component swapping, combinatorial, bus, sectional, and fabricate-to-fit modularity. The high degree of modularity of a product allows variety to be created at the final assembly, usually the last stage of the production process. This has profound implications for the selection of decoupling points for products showing high degrees of modularity in their product structures.

The importance of product variety in relation to the selection of decoupling points lies in the fact that the way in which product variety is delivered has a strong impact on where, how, and when in the value chain, the product is customized. The knowledge model (that will be shown as Fig. 5) captures knowledge related to product variety in the engineering and design, materials and parts procurement, manufacturing, and assembly knowledge domains.

3.3.3 Product differentiation and product postponement

Value is added to a product as it passes through different value-adding stages in the value chain from concept generation to the end of its lifecycle. Usually, early supply chain processes, and the parts of a product family that flow, are common to the majority of the variants of a product family. Different product variants are generally differentiated from each other at the later stages of the chain when distinguishing features are added. Product differentiation refers to the value-adding activities that give a product variant its distinctive features and differentiates it from other members of its family.

Postponement of the point of product differentiation is an important means of reducing supply chain risk and uncertainty [**22**]. The delaying of product differentiation closer to the end customer is known as product postponement or delayed differentiation. The concept was originally introduced by Alderson [**23**]. Bowersox *et al.* [**1**] identified two ways in which product postponement can occur: manufacturing postponement and logistics postponement.

In manufacturing postponement, postponed semi-finished products undergo changes in form and identities after the point of postponement, once real orders have been placed. In logistics postponement, on the other hand, postponed finished products undergo only changes in inventory location after the point of postponement, again, once real orders have been placed. By postponing the customisation of products, organisations can gain a number of advantages. These include the ability to hedge against uncertain customer demand since aggregate demand forecasts tend to be more accurate than disaggregate demand data, reduced risk of product obsolescence, more opportunities for economies of scale, reduced inventory and logistics costs, and reduced imbalance in stock distribution. However, product postponement also poses a number of disadvantages. These include the loss of economies of scale for any particular finished product variant and a need for increased agility in supply chain stages after the point of postponement. The knowledge model (that will be shown as Fig. 5) captures knowledge related to product differentiation and product postponement in the engineering and design, manufacturing, assembly, and storage–distribution–logistics knowledge domains. For example, for product differentiation and postponement, the type of product structure (e.g. modular or integral) and the available flexibility in the production processes are captured.

3.3.4 *Component and part commonality*

Component and part commonality was identified by Lee [**24**] and Lee and Tang [**25**] as a means of implementing product postponement. One or more may be appropriate depending upon the specific issues that need to be addressed.

The use of component and part commonality involves the sharing of components, parts, and subassemblies across multiple variants in a product family to reduce the total number of distinct components and parts that need to be managed by an organization and its supply chain. Risk pooling and reduction in lead time uncertainty are two major benefits of commonality that can lead to safety stock reduction [**22**]. According to Lee [**24**]

> A powerful benefit of part commonality, often ignored in the literature is that it can be used as means to achieve delayed product differentiation.

Increased commonality of components and parts provides greater opportunities for delaying product differentiation closer to the end customer, as customized product variants can be created by adding customized parts to a generic semi-finished product body (made up of common parts) of a product family in the latter stages of manufacturing and assembly. The knowledge model (that will be shown as Fig. 5) captures knowledge related to component and part commonality in the engineering and design, materials and parts procurement, manufacturing, and assembly knowledge domains.

3.3.5 *Component and part standardization*

Standardization occurs when a component or part implements commonly useful functions and has identical interfaces across more than one product. Ulrich [**20**] argues that a high degree of modularity in the product structure makes standardization possible. For products exhibiting high degrees of modularity in product structure, each component or part implements exactly one function and *vice versa*. Commonality in the occurrence of such functions, as well as identical component and part interfaces across multiple product variants, makes their associated parts and components useful across multiple products. These enable component and part standardization for highly modular product structures. On the other hand, a high degree of integral product structure poses limited opportunities for component and part standardization – for them standardization is possible only if several product variants implement exact combinations of functional elements or parts of functional elements. Standardization enables a semi-finished common product body to be created using standard components and parts which can later be customized by adding customized parts or components as soon as real customer order data is available. Standardization facilitates postponement of product differentiation until the last stages of the manufacturing process or even closer to the end customer. The knowledge model (that will be shown as Fig. 5) captures knowledge related to component and part standardization in the engineering and design, materials and parts procurement, manufacturing, and assembly knowledge domains.

4 A KNOWLEDGE–BASED APPROACH FOR SELECTION OF SUPPLY CHAIN DECOUPLING POINTS

The selection of customer order decoupling points in supply chains is a strategic decision made by decision makers who are formulating supply chain operation strategies. The choice of the location for a decoupling point in a supply chain has far-reaching impacts on supply chain performance. The decision is best taken with consideration of the views and knowledge of multiple domain experts and from all three tiers of the decision hierarchy: strategic, tactical, and operational. Knowledge-based tools have been applied in a number of application areas where information from a number of domain experts and perspectives is used to come to a decision. This is the case with the selection of supply chain decoupling points.

Features and functionalities of knowledge-based tools vary widely. In their very simplest form, a knowledge-based tool has two modules: a knowledge module (often referred to as a knowledge base) where domain knowledge is captured and a control module (often implemented as an inference engine) that infers results using the domain knowledge and inputs from the user. There is also a user interface.

A key aspect of any application of knowledge-based technologies is the knowledge model that sits at its heart. Shadbolt and Milton [**26**] assert that knowledge acquisition includes elicitation, collection, analysis, modelling, and validation of knowledge. This section defines the knowledge model that was built for the purpose of this research and aligns with the model put forward by Shadbolt and Milton [**26**]. The following process steps were used to create the knowledge model.

1. Identification of knowledge domains that influence supply chain decoupling point selection.
2. Elicitation of domain knowledge from the identified knowledge domains.
3. Modelling and representation of the extracted knowledge.
4. Development of a rule network or inference tree to process this knowledge.
5. Encoding of the acquired knowledge in an experimental knowledge base.
6. Development of a fact base and use of the knowledge base (through case study implementations) for problem solving using the experimental software prototype.

These process steps were used to develop a model and form the structure of this section of the paper. The use of the knowledge base in a case study implementation is described in section 5.

4.1 Identification of knowledge domains

The first step in the development of a knowledge model involves identifying the knowledge domains that influence the decision to be supported: in this case, the selection of the position of a supply chain decoupling point. For the purposes of this research, these domains were taken to be the key supply chain operation processes, namely, engineering and design, raw materials and parts procurement, manufacturing, assembly, storage–distribution–logistics, and retail sales and marketing. The possible strategic

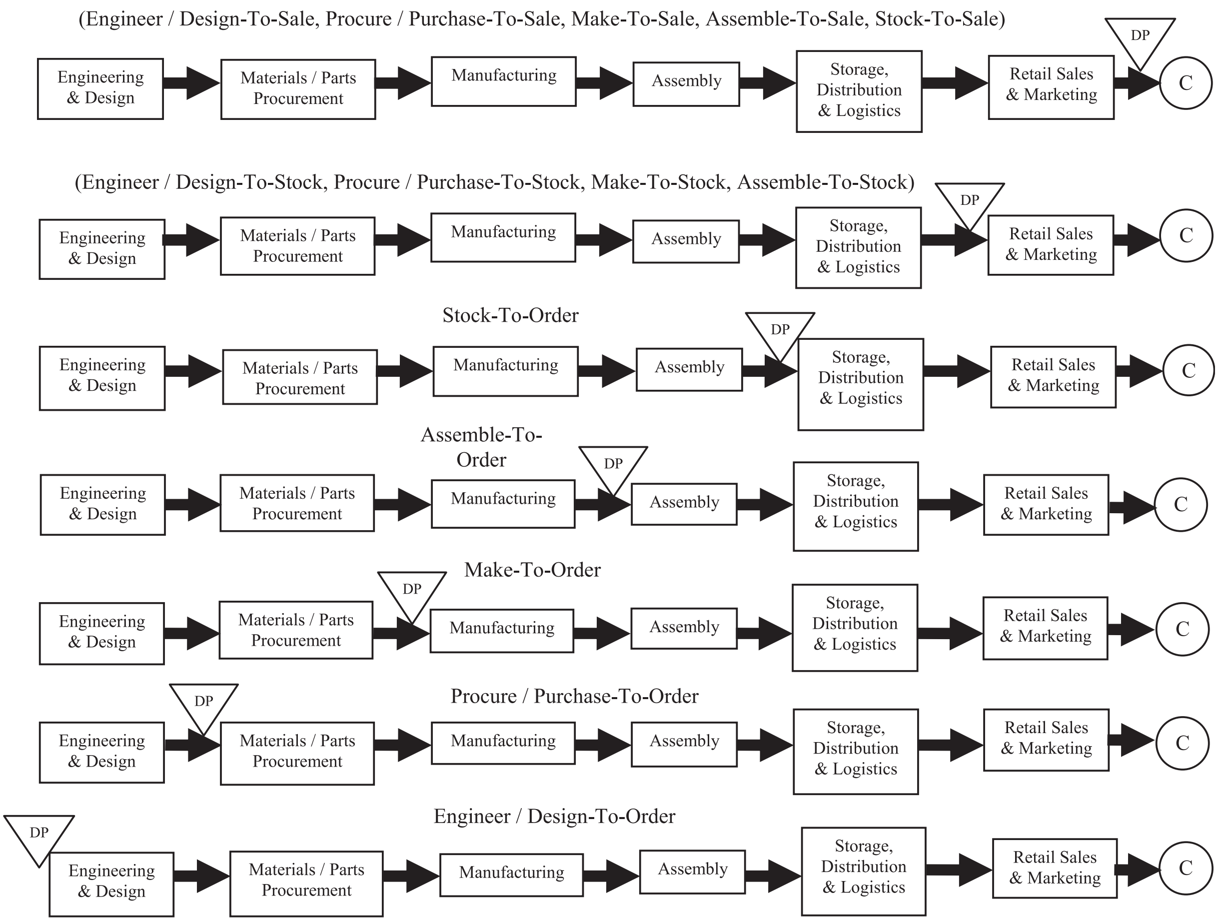

Fig. 4 Supply strategies and possible locations of decoupling points

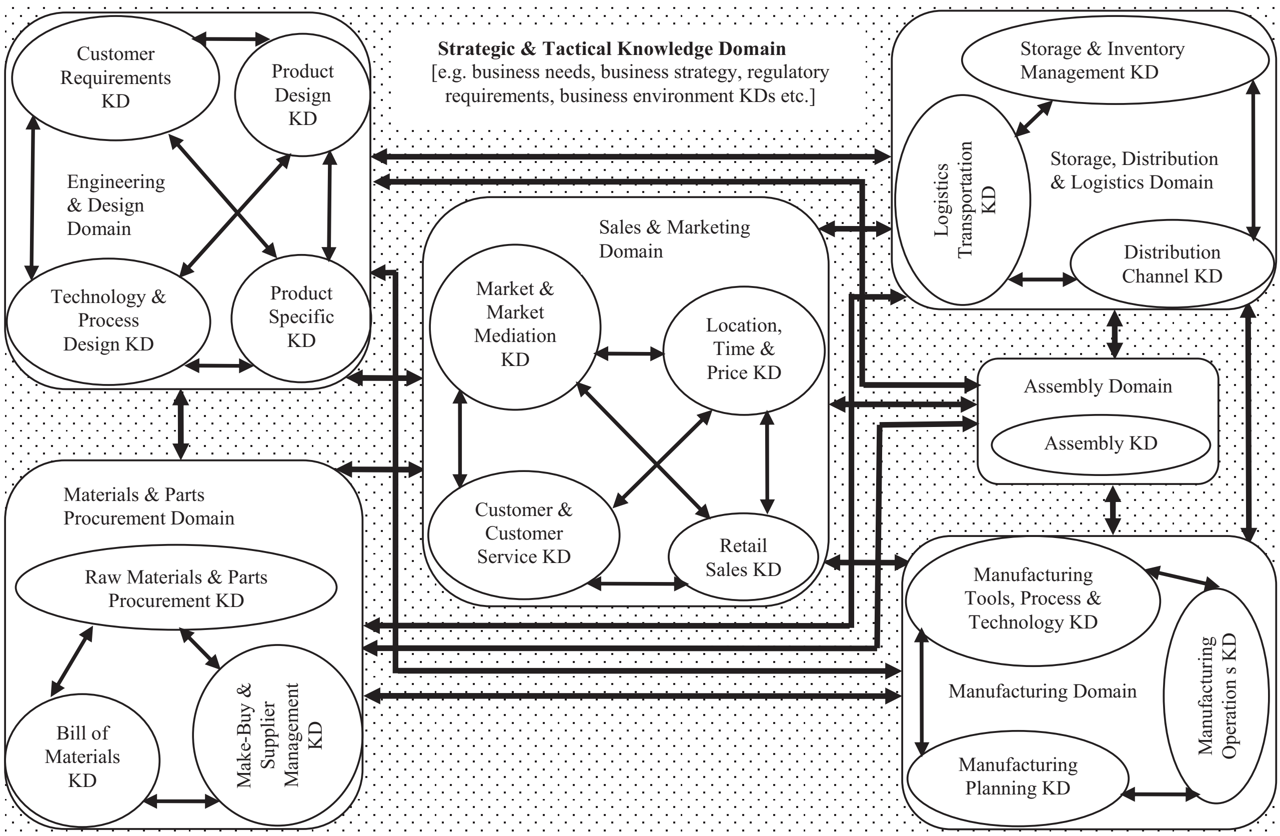

Fig. 5 Major knowledge domains and subdomains to be considered for making supply chain decisions

locations of decoupling points in a manufacturing supply chain are shown schematically in Fig. 4. These are depicted in the figure by triangles between different stages of supply chain operation. The arrow directions represent the directions along which supply chain operations sequentially proceed. The end customer is represented by the letter ‘C’ in a circle.

In each of the stages of a supply chain operation, decisions are made that can influence the location of the decoupling point in the supply chain as a whole. There are three levels in a supply chain decision hierarchy: strategic, tactical, and operational. Though it is difficult to draw sharp lines between different levels of decisions in the decision hierarchy, higher level decisions can override lower level decisions (that is, strategic assumes more importance than tactical and operational and tactical assumes more importance than operational decisions).

Experts take decisions based on their domain knowledge. A schematic showing major knowledge domains and subdomains that are taken into consideration for making supply chain decisions in this research is given in Fig. 5. The figure shows (in the six rounded rectangles) engineering and design, materials and parts procurement, manufacturing, assembly, storage–distribution–logistics, and sales and marketing as the major knowledge domains. The overall strategic and tactical knowledge domain is represented by the large shaded outer rectangle and is applicable to the entire supply chain. Each of the major knowledge domains shown in the diagram has a number of subdomains. A selection of typical knowledge subdomains are shown as circles and ellipses for each of the major knowledge domains in Fig. 5. The black double arrowed lines connecting various knowledge domains and subdomains represent links and overlaps between them. This research demonstrated how viewpoints and knowledge from the different experts’ domains and subdomains shown in Fig. 5 might be exploited to aid in the selection of supply chain decoupling points.

4.2 Knowledge elicitation

Once the knowledge domains have been identified, knowledge is elicited from each domain. Several techniques have been developed to help elicit knowledge from an expert. Schreiber *et al.* [**27**] assert that knowledge elicitation can be seen as providing the material for knowledge modelling. Table 1 shows the knowledge resources that were used to elicit domain knowledge for this research.

Table 1 Knowledge domains and corresponding knowledge resources

Sources		Knowledge domains: Engineering and design	Raw materials and parts procurement	Manufacturing	Assembly	Storage-distribution-logistics	Retail sales and marketing
Review of published literature, publicly available reports, brochures, case studies, websites	[**9**, **19**, **20**, **22**, **24**, **25**, **28–30**]	x					
	[**31**]		x				
	[**32**], www.cannondale.com[8]					x	
	[**1**],[**33**], [**34**]			x	x		
	[**12**, **35–37**]		x			x	
Informal interviews, discussions and participation in workshops with the domain experts							x
Onsite industrial visits, observation and commentating	(i) Chevin Cycles of Otley, Leeds (ii) Stif Mountain Bikes of Headingley, Leeds					x	x
Publicly available multimedia materials such as video footage and presentations downloaded from the websites	www.cannondale.com[**8**]			x	x		

Table 2 Product architecture and component process flexibility dictate the economics of producing variety (reproduced from Ulrich, [**20**])

Product architecture		
Modular	1. Variety can be achieved by combinatorial assembly from relatively few component types 2. Can assemble to order from component inventories 3. Minimum order lead time dictated by final assembly process	1. May fabricate components to order as well as assemble to order 2. May choose to carry component inventories to minimize order lead time 3. Infinite variety is possible when components are fabricate to order
Integral	1. High variety not economically feasible; would require high fixed costs (e.g. tooling), high set-up costs, large order lead times, and/or high inventory costs	1. Variety can be achieved without relatively high inventory costs by fabricating components to order 2. Minimum order lead times dictated by both component fabrication time and final assembly time 3. Infinite variety is possible
	Low	High
	Component process flexibility	

4.3 Modelling and representation of extracted knowledge

Schreiber *et al.* [**27**] asserted that the task of knowledge modelling is to convert the elicited material into a formal description of the problem solving process. The knowledge representation scheme adopted for this research comprised production rules and facts. Knowledge extracted from domain experts was analysed using simple reasoning techniques with a view to answering the following questions.

1. What decisions are taken in particular situations and why are those decisions taken?
2. What actions are taken in particular situations and why are those actions taken?

The collected domain knowledge was analysed to identify causes and effects. Rules relating causes and effects (of the form *Cause* + *Effect* => *Rule*) were represented as IF....THEN..... statements in pseudo-code, where the condition part of the statement (the 'IF' part) represented the cause and the inference part (the 'THEN' part) represented the effect. Logical connectives such as AND, OR, and NOT were used to capture compound aspects of the rules. The process used to model the extracted knowledge is outlined at the end of section 4 and will be illustrated in Fig. 7.

For example, in [**20**], Ulrich diagrammatically represented relationships between product architecture, component (manufacturing) process flexibility, economics of producing variety, and manufacturing strategy. This is reproduced in Table 2. In this table domain knowledge is represented tacitly. For example, it can be observed and interpreted from Table 2 that with a modular product architecture and low component (manufacturing) flexibility, product variety can be achieved by combinatorial assembly from relatively few component types. This observation has two parts – condition and inference. The condition part is represented by – '... with a modular product architecture and low component (manufacturing) flexibility'. The inference part is represented by – 'variety can be achieved by combinatorial assembly from relatively few component types'. The 'condition' part represents the cause, while the 'inference' part represents the effects of a production rule. This condition and corresponding inference can be formally represented as a production rule using 'IF' before the condition part and 'THEN' before the inference part. The condition and inference introduced in this example are formally represented in Rule 45.3 in Table 3 as

> IF Product P_1 has a modular product structure AND manufacturing process flexibility is low for product P_1, THEN variety can be achieved economically for P_1 by combinatorial assembly from relatively few component types.

4.4 Development of the rule network

Knowledge gathered from different experts' domains was represented in the form of production rules. A small number of the (total of 236) rules developed in this research are presented in Table 3 as examples. In Table 3, each rule is given a unique identification having two numerical parts separated by a decimal point (e.g. 43.1, 43.2, 42.2, and 42.3). Qualifiers such as 'a lot of', 'high', 'low', 'very high', and 'few' are often used in the rules instead of quantitative values or a range of values. These qualifiers are case study specific and had to be quantified for implementation purposes.

The domain rules from different knowledge domains were analysed to identify interrelationships and, where possible, these interrelationships were represented in a rule network. This logical network of rules underpinned the rule base of the experimental software prototype. A small fragment of the rule network is depicted in Fig. 6.

Table 3 Examples of domain rules

Rule	IF (pattern/condition)	THEN (action/inference)
42.1	Flexibility of assembly sequence is high AND assembly cost is low for product P_1	Flexibility of assembly system is high for P_1
42.2	Flexibility of assembly sequence is high AND assembly cost is high for product P_1	Flexibility of assembly system is low for P_1
42.3	Flexibility of assembly sequence is low AND assembly cost is low for product P_1	Flexibility of assembly system is low for P_1
42.4	Flexibility of assembly sequence is low AND assembly cost is high for product P_1	Flexibility of assembly system is low for P_1
43.1	Fixed tooling cost is low AND change-over cost is low for small lot size for product P_1	Manufacturing processing cost is low for P_1
43.2	Fixed tooling cost is high AND change-over cost is low for small lot size of product P_1	Manufacturing processing cost is high for P_1
43.3	Fixed tooling cost is low AND change-over cost is high for small lot size for product P_1	Manufacturing processing cost is high for P_1
43.4	Fixed tooling cost is high AND change-over cost is high for small lot size for product P_1	Manufacturing processing cost is high for P_1
43.5	Fixed tooling cost is low AND change-over cost is low for large lot size for product P_1	Manufacturing processing cost is high for P_1
43.6	Fixed tooling cost is high AND change-over cost is low for large lot size for product P_1	Manufacturing processing cost is high for P_1
43.7	Fixed tooling cost is low AND change-over cost is high for large lot size for product P_1	Manufacturing processing cost is high for P_1
43.8	Fixed tooling cost is high AND change-over cost is high for large lot size for product P_1	Manufacturing processing cost is high for P_1
44.1	Flexibility of assembly system is high for product P_1 AND flexibility of process equipment is high for product P_1 AND manufacturing processing cost is low for product P_1	Manufacturing process flexibility is high for P_1
44.2	Flexibility of assembly system is low for product P_1 AND flexibility of process equipment is high for product P_1 AND manufacturing processing cost is low for product P_1	Manufacturing process flexibility is low for P_1
44.3	Flexibility of assembly system is high for product P_1 AND flexibility of process equipment is low for product P_1 AND manufacturing processing cost is low for product P_1	Manufacturing process flexibility is low for P_1
44.4	Flexibility of assembly system is low for product P_1 AND flexibility of process equipment is low for product P_1 AND manufacturing processing cost is low for product P_1	Manufacturing process flexibility is low for P_1
44.5	Flexibility of assembly system is high for product P_1 AND flexibility of process equipment is high for product P_1 AND manufacturing processing cost is high for product P_1	Manufacturing process flexibility is low for P_1
44.6	Flexibility of assembly system is low for product P_1 AND flexibility of process equipment is high for product P_1 AND manufacturing processing cost is high for product P_1	Manufacturing process flexibility is low for P_1
44.7	Flexibility of assembly system is high for product P_1 AND flexibility of process equipment is low for product P_1 AND manufacturing processing cost is high for product P_1	Manufacturing process flexibility is low for P_1
44.8	Flexibility of assembly system is low for product P_1 AND flexibility of process equipment is low for product P_1 AND manufacturing processing cost is high for product P_1	Manufacturing process flexibility is low for P_1
45.1	Product P_1 has a highly modular product structure AND manufacturing process flexibility is low for product P_1	Variety can be achieved economically for P_1 by combinatorial assembly from relatively few component types
45.2	Product P_1 has a highly modular product structure AND manufacturing process flexibility is high for product P_1	High variety can be achieved economically for P_1 by making-components-to-order OR assembling-components-to-order
45.3	Product P_1 has a modular product structure AND manufacturing process flexibility is low for product P_1	Variety can be achieved economically for P_1 by combinatorial assembly from relatively few component types
45.4	Product P_1 has a modular product structure AND manufacturing process flexibility is high for product P_1	High variety can be achieved economically for P_1 by making-components-to-order OR assembling-components-to-order
45.5	Product P_1 has an integral product structure AND manufacturing process flexibility is high for product P_1	High variety can be achieved without relatively high inventory cost for P_1 by making-components-to-order
45.6	Product P_1 has an integral product structure AND manufacturing process flexibility is low for product P_1	High variety for P_1 is not economically feasible
45.7	Product P_1 has a highly integral product structure AND manufacturing process flexibility is high for product P_1	High variety can be achieved without relatively high inventory cost for P_1 by making-components-to-order
45.8	Product P_1 has a highly integral product structure AND manufacturing process flexibility is low for product P_1	High variety for P_1 is not economically feasible

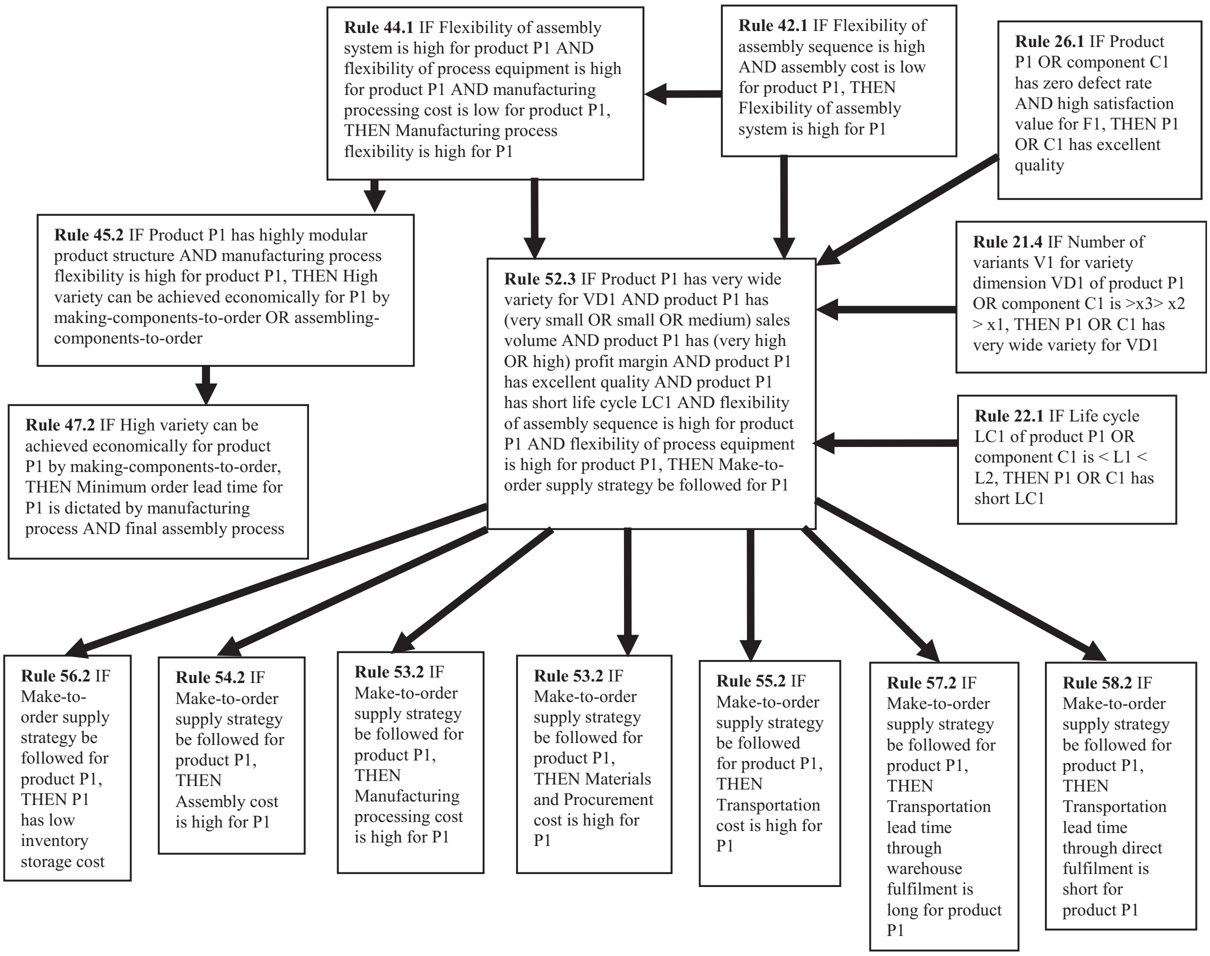

Fig. 6 A small fragment of the rule network showing logical dependencies among domain rules

4.5 Encoding of acquired knowledge to build a knowledge base

Knowledge acquired in the form of production rules from multiple experts' knowledge domains was encoded using the Jess (Java Expert System Shell) language to build a rule base (i.e. the knowledge base) for the experimental software prototype.

4.6 Development of fact base and use of the knowledge base for problem solving

The knowledge base was developed to demonstrate the feasibility of applying knowledge-based approaches to the selection of supply chain decoupling points. In this section the way in which the knowledge base might be used to support the selection of supply chain decoupling points is outlined. The development of a fact base and use of a knowledge base for the selection of decoupling points in a specific supply chain are demonstrated in Section 5. A Cannondale bicycle supply chain was used as the case study; a typical scenario of a Cannondale bicycle supply chain is described in section 3.

Figure 7 shows, using use case diagrams in UML, the functions it is anticipated would be performed for the selection of decoupling points in a given supply chain. At the beginning of the selection process a knowledge engineer would acquire domain knowledge. This knowledge acquisition activity includes two subfunctions: elicitation of knowledge from knowledge sources (such as domain experts), and modelling and representation of acquired knowledge as domain rules using pseudocodes. Next, the user of the Protégé-Jess-JessTab tool would build a rule base (or knowledge base). This would include the encoding of domain rules into Jess codes. Once this had been done, the user of the Protégé-Jess-JessTab tool would insert known facts to build a fact base. This includes encoding of known facts into Jess codes. The user of the Protégé-Jess-JessTab tool would then run the inference engine within the Protégé-Jess-JessTab tool. This would be followed by two functions performed in sequence: firing of the activated rules (in the rule base) on known facts (in the fact base), and then the generation of new facts in the fact base. The old (i.e. known) and

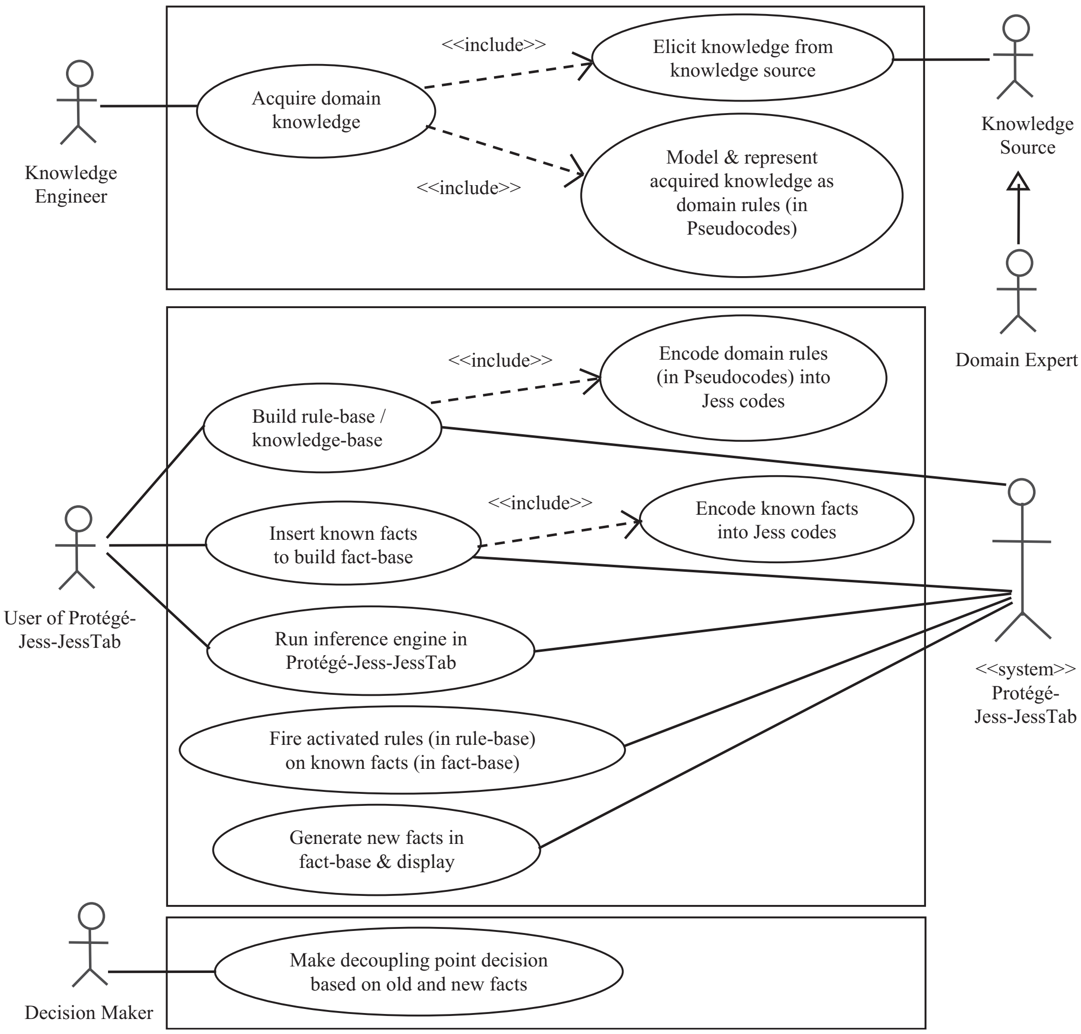

Fig. 7 Functions performed in sequence for selection of supply chain decoupling points

new (generated) facts would be presented to the decision maker who would use them to inform decisions regarding the positioning of the decoupling points in the chain.

5 CASE STUDY

A picture of a Jekyll 3000 model mountain bike is given in Fig. 8 and a schematic description of a supply chain structure for a Jekyll 3000 model mountain bike is provided in Fig. 9. In Fig. 9, individual organizations are represented by rounded rectangles, groups of organizations are shown in octagons, and the ellipse represents end users. The arrows represent customer–supplier relationships between organizations in the supply chain. In the supply chain, products and services flow in the directions of the arrows and demands flow in the other direction, from arrow tail to arrow head; information flows in both directions. The supply chain represented in the diagram is a manufacturing supply chain in which

Fig. 8 A Jekyll 3000 model mountain bike (courtesy www.cannondale.com)

Cannondale is the brand-owner. For convenience, Cannondale's design and procurement sections, their manufacturing plant, and their bike assembly plant have been represented as separate organizations in

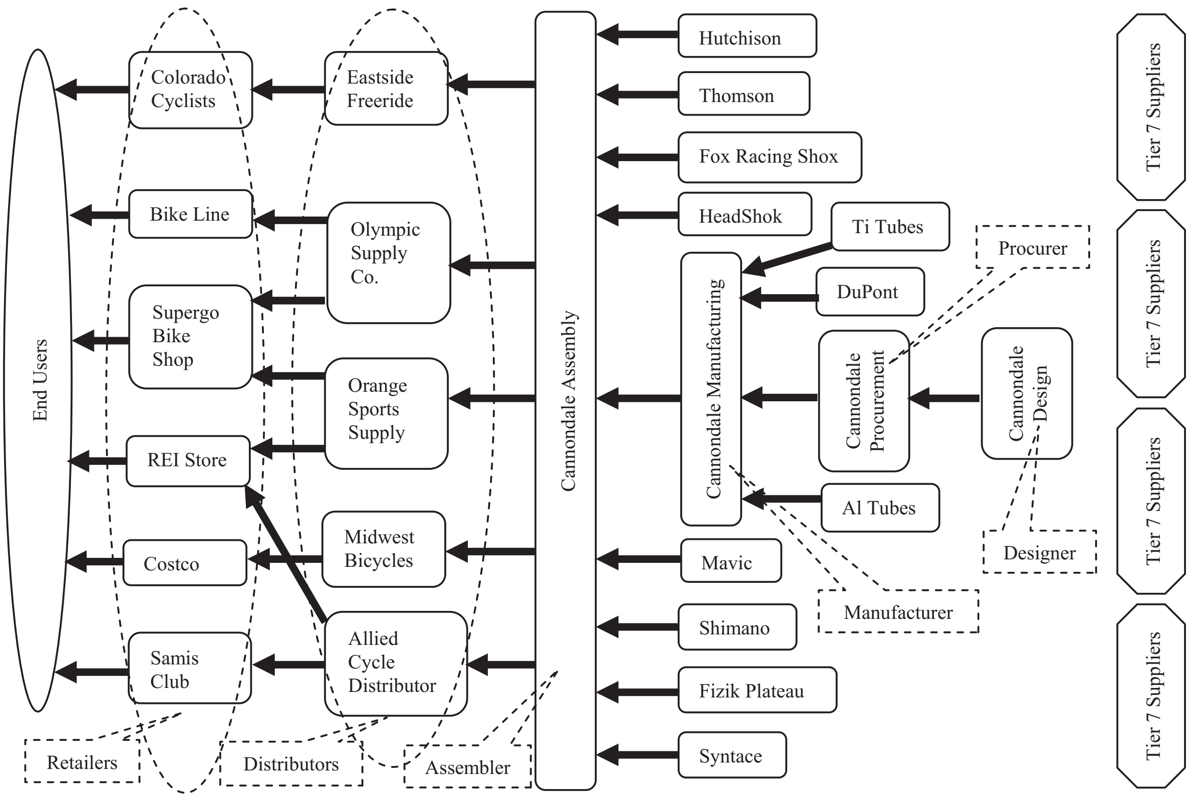

Fig. 9 A supply chain structure for Cannondale's Jekyll 3000 model mountain bike

the supply chain structure. Also, for simplification, Tier 7 or higher tier suppliers are not taken into account in the supply chain structure described by the diagram. The supply chain structure, described in Fig. 9 for the Jekyll 3000 model mountain bike, shows six operational stages: engineering and design, procurement, manufacturing, assembly, storage–distribution–logistics, and retail sales.

Data from the case study were input as known facts in the experimental software prototype using Jess to populate the fact base. As facts were asserted, rules (in the rule base) whose conditional parts matched the input facts were activated. This generated new facts which were also stored in the fact base and used to activate rules.

In each case, new or derived facts were generated when new facts caused rules in the rule base to be fired. This iterative process stops when no more new facts are generated. In each experimental run, the input and newly generated facts were used to suggest a supply strategy and its implications.

6 RESULTS

Four experimental runs of the software prototype were made with this case study, each with a different set of input data. Key results are summarized in Tables 4 to 6. In Tables 4 to 6 the following conventions are used:

(a) data in bold is actual data input to the tool, e.g. 5;
(b) data range within brackets defines a range of a key benchmark, e.g. 'medium' is defined by the value range (10–20).

Table 4 lists the conditions under which the software prototype suggested a supply strategy. These conditions were either originally input facts or facts derived from the input facts through the rule network. Table 5 gives the supply strategy suggested by the experimental prototype under the conditions given. Table 6 gives predicted (suggested by the software) values (or range of values) for a number of supply chain performance indicators for the suggested supply strategy and the given set of conditions. This information could be used to inform the positioning of the decoupling points in supply chains. Possible locations of decoupling points for different supply strategies are shown in Fig. 4.

The results from these experimental runs were used to visualize trends in cost and lead time that occur as parameter values were changed. Figures 10, 11, and 12 show the impact of key parameters on unit cost whereas Figs. 13 and 14 show the impact of the same parameters on lead time. In Figs 10 to 14,

Table 4 Conditions (key asserted facts and/or facts derived from asserted facts)

Experimental tool run	Run 1	Run 2	Run 3	Run 4
Inference / search strategy used by the tool	Depth First	Depth First	Depth First	Breadth First
Product	Jekyll 3000 Mountain Bike			
Product Structure (degree of modularity) (in numerical index of 4 -1)	Integral **2**	Modular **3**	Modular **3**	Highly Modular **4**
Product variety (Variety dimension: frame geometry)	One-of-type design ∞	Very wide **12** (11–15)	Wide **8** (7–10)	Narrow **2** (1–3)
Sales volume	Very small **8** (1–20)	Small **75** (21–100)	Medium **300** (101–400)	Large **2000** (401–∞)
Profit margin (in % of cost)	Very high **55** (41–∞)	High **37** (30–40)	Medium **23** (20–29)	Low **12** (1–19)
Product quality (in numerical index of 4 -1)	Excellent **4**	Excellent **4**	High **3**	Medium **2**
(Average) Product lifespan in the market (in months)	Short **9** (6–15)	Short **12** (6–15)	Medium **18** (16–24)	Long **36** (25–∞)
Assembly sequence flexibility	x	High	High	High
Flexibility of manufacturing processing equipment	x	High	x	High

Table 5 Supply strategy suggested (by the software prototype)

Experimental tool run	Run 1	Run 2	Run 3	Run 4
Supply strategy suggested by the software prototype	Engineer-to-order supply strategy	Make-to-order supply strategy (alternately, variety can be achieved by combinatorial assembly from few component types)	Assemble-to-order supply strategy	Engineer-to-stock / procure-to-stock / make-to-stock / assemble-to-stock supply strategy (alternately, high variety can be achieved economically by either assemble-to-order or make-to-order from components)

the following abbreviations are used: ETO implies engineer to order, MTO implies make to order, ATO implies assemble to order, MTS implies make to stock. In general some trends can be seen. For example, it can be seen from Figs 10, 12, and 13 that as the order volume and product lifespan[4] in the market increase, the cost per unit decreases as does the transportation lead time – in such situations the prototype software suggested more physically efficient rather than responsive supply strategies. On the other hand, it can be seen from Figs 11 and 14 that as the product variety increases, the cost per unit increases as does the transportation lead time – in such situations the prototype software suggested more responsive rather than physically efficient supply strategies.

[4]*Length of time for which a given product variant is made available on the market.*

7 DISCUSSION

The research reported in this paper developed a knowledge model that supports the capture of multiple view points and factors influencing decoupling

Table 6 Implications (on supply chain performance indicators if the suggested supply strategy be considered)

Experimental tool run	Run 1	Run 2	Run 3	Run 4
Manufacturing processing cost (in $ per unit)	Very high (401-∞)	High (161-400)	Medium (71-160)	Low (25-70)
Assembly cost (in $ per unit)	Very high (201-∞) [in run 1, run 2, run 3 and run 4]			
Materials and procurement cost (in $ per unit)	Very high (1201-∞)	High (501-1200)	Medium (201-500)	Low (75-200)
Transportation cost (in $ per unit)	Very high (100-∞)	High (51-99)	Medium (21-50)	Low (1-20)
Inventory storage cost (in $ per unit)	Low (1-10)	Low (1-10)	Medium (11-20)	High (21-∞)
Transportation lead time through warehouse fulfillment (in weeks)	Long (>2)	Long (>2)	Medium (1-2)	Short (<1)
Transportation lead time through direct fulfillment (in weeks)	Medium (1–2)	Short (<1)	Short (<1)	x

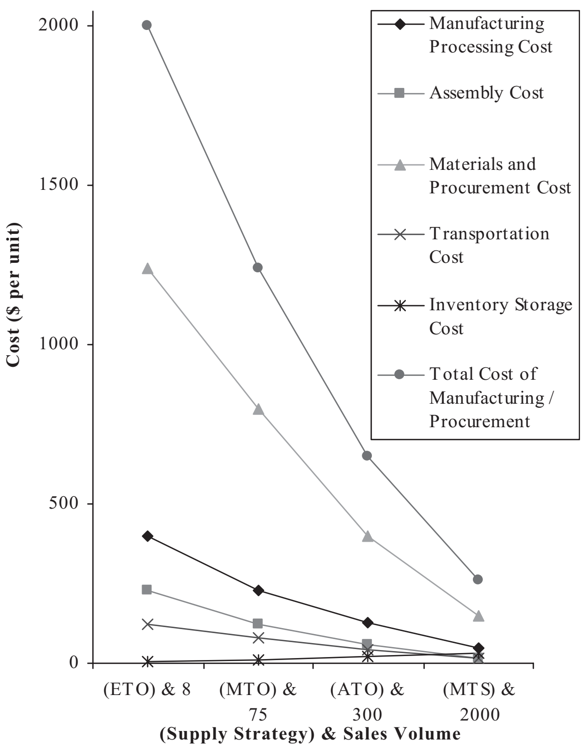

Fig. 10 Cost versus sales volume and supply strategy

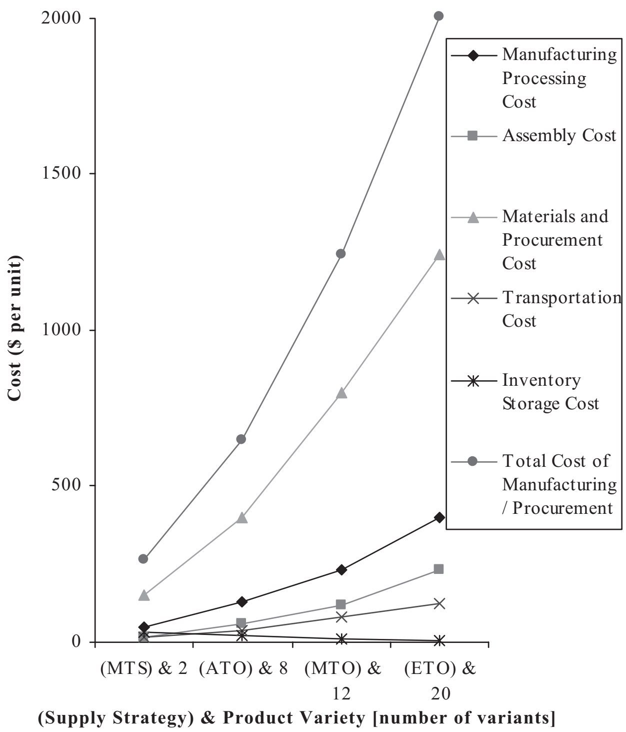

Fig. 11 Cost versus product variety and supply strategy

point selection in supply chains. The model underpins the rule base developed for the experimental software prototype. The experimental software prototype provides gross predictions regarding potential manufacturing and procurement costs (including manufacturing processing, assembly, materials, transportation, and inventory storage) and lead time for the product under consideration, if the supply strategy suggested by the experimental software prototype be used under the given set of conditions. Trends can be observed in key engineering and supply chain parameters of a product and the supply strategies suggested by the software prototype. Trends can also be observed in the suggested supply strategies for a product and the corresponding cost and lead time parameters. Relationships between the aforementioned two types of trends can be established using the common factor, the suggested supply strategy. For example, it can be seen from Tables 4 to 6 and Figs 10 to 14, that with increases

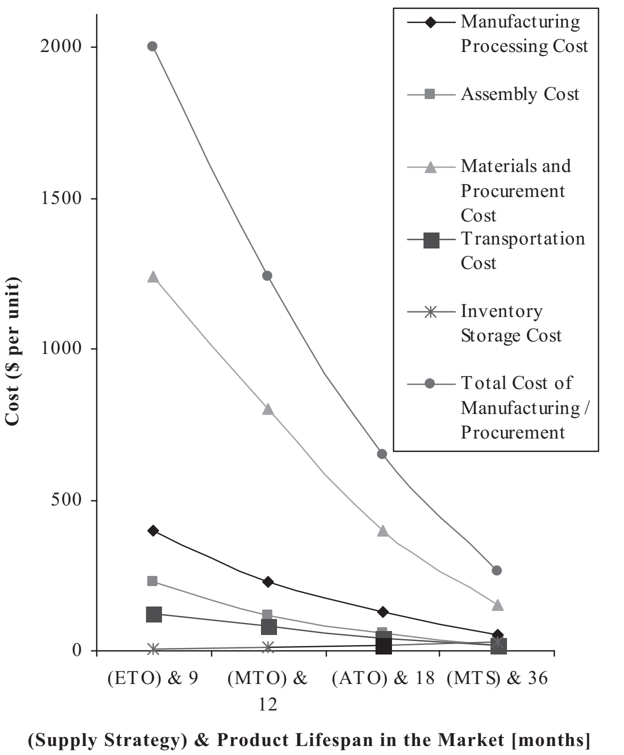

Fig. 12 Cost versus product lifespan in the market and supply strategy

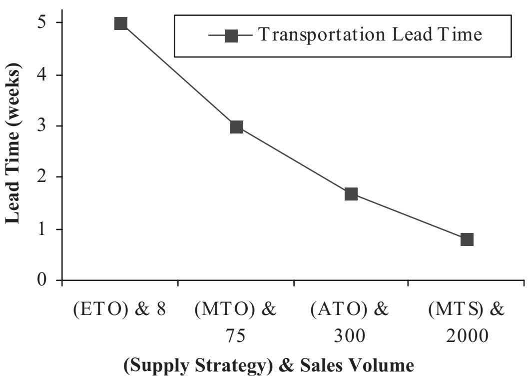

Fig. 13 Lead time versus sales volume and supply strategy

in product variety, profit margin and product quality, and decrease in sales volume (or order quantity) and product lifecycle, the total cost of manufacturing and procurement (per unit) and transportation lead time (and thereby delivery lead time) increases; with such trends the software prototype suggested supply strategies that tend to be more market responsive rather than physically efficient. By making supply strategy more market responsive, high risk of obsolescence and high inventory costs can be hedged. In contrast, high degrees of modularity in product structure and manufacturing process flexibility enhance

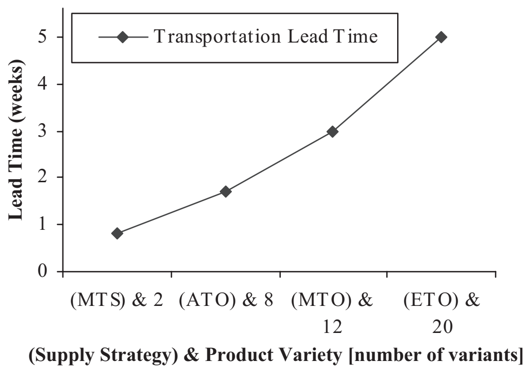

Fig. 14 Lead time versus product variety and supply strategy

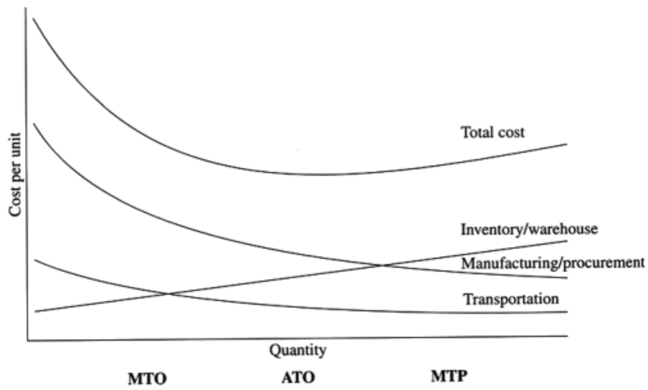

Fig. 15 A generalized model of the total cost of manufacturing and procurement showing trends in cost–quantity–supply strategy relationships (reproduced from Bowersox *et al.* [**1**], p. 94)

opportunities for delivering variety economically and provide opportunities for postponement of product customization closer to the end customer. It can also be observed from the table that as inventory is kept closer to the end customer and in more finished forms, the inventory and storage costs go up.

One way of evaluating the rule base and its underlying model is by comparing the results from the software prototype against those reported in the literature. The results obtained from the application of the experimental software prototype to the Cannondale bicycle supply chain case study were compared with those reported by Bowersox *et al.* [**1**]. Bowersox *et al.* [**1**] presented a generalized model of the total cost of manufacturing and procurement[5] (per unit) ranging across strategic alternatives from

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[5] *According to Bowersox et al., [1], the total cost of manufacturing is the sum of inventory / warehouse cost, manufacturing / procurement cost, and transportation cost of a product.*

Table 7 A strategic integration framework showing critical relationships between market distribution, manufacturing/procurement, and logistical relationships (reproduced from Bowersox *et al.* [**1**], p. 96)

Market drivers	Manufacturing capabilities	Procurement	Logistics
Focused: One-on-one strategies Unique product/service offerings Response-based	**Make-to-Order:** Maximum variety Unique configuration Flexible manufacturing High variety	**B2B** Discrete quantities Supplier VMI	**Direct fulfillment:** Time postponement Small shipment
Segmental: Limited size Customer groups Differentiated products Mixed response and anticipatory	**Assemble-to-Order:** Wide variety Quick changeover Product customization High variety and volume	**B2B** JIT	**Form and time postponement:** Warehouse ATO Combination of direct and warehouse fulfillment
Mass marketing: Anticipatory Little product differentiation	**Make-to-Plan:** Long product runs Focus low cost High volume/low variety	**B2B** Commodity Auction E-procurement	**Warehouse fulfillment:** Full stocking strategy Assortment mixing Volume shipment

make to order through assemble to order to make to stock (or make to plan or MTP). This is represented in Fig. 15. The figure shows that cost of manufacturing and procurement declines as quantity increases, reflecting economies of scale associated with make to stock; inventory and warehousing costs increase, reflecting the impact of large manufacturing lot size; transportation cost per unit decreases as a result of shipment consolidation. In contrast, the make-to-order strategy reflects higher per unit manufacturing and procurement costs which are, in part offset by lower inventory and warehousing costs. In the make-to-order strategy, the transportation cost per unit is higher reflecting small shipment and premium transportation. Figure 15 depicts generalized trends and relationships between different costs and supply (or order) quantity for different supply strategies. Bowersox *et al.* [**1**], asserted that the total cost of manufacturing and procurement results from functional integration of manufacturing, procurement, and logistics.

Analysis of Tables 4 to 6 and Fig. 10 reveals generalized trends and relationships between different costs and supply (or order) quantity for different supply strategies. The trends show that as sales (or order) quantity increases, the manufacturing and procurement cost[6] declines, reflecting economies of scale associated with engineer to stock, procure to stock, make to stock, and assemble to stock; inventory storage cost increases reflecting the impact of large manufacturing lot size; and transportation cost per unit decreases as a result of shipment consolidation. In contrast, engineer-to-order and make-to-order strategies reflect high per unit manufacturing and procurement costs which are, in part offset by lower inventory and warehousing costs. Also, in the engineer-to-order and make-to-order strategies, the transportation cost per unit is higher reflecting small shipment and premium transportation. For these reasons, it can be concluded that key results output (shown in Fig. 10) from application of the software prototype to the case study show similar trends in cost–quantity–supply strategy relationships as those (shown in Fig. 15) reported in literature by Bowersox *et al.* [**1**].

Bowersox *et al.* [**1**], also presented a strategic integration framework (shown in Table 7) that shows the critical relationships between market distribution, manufacturing, procurement, and logistical requirement. The following can be observed.

1. The make-to-order strategy and small shipment through direct fulfillment are suitable for high (or maximum) product variety, flexible manufacturing, unique product / service offerings, and unique product configuration conditions.
2. The assemble-to-order strategy and consolidated shipment size through a combination of warehouse and direct fulfillment are suitable for wide product variety, differentiated products, high volume, and quick changeover in manufacturing and assembly conditions.

A make-to-stock or make-to-plan strategy and volume shipment through warehouse fulfilment are suitable for low product variety, high volume,

[6] *Manufacturing and procurement cost is the sum of manufacturing processing cost, assembly cost, and materials and procurement cost.*

low-cost commodity, and long production run conditions.

Results obtained from the application of the software prototype to the Cannondale bicycle supply chain case study show similar trends in relationships between product variety, product volume, manufacturing and assembly flexibility, product quality and supply strategy, and logistical fulfillments strategies. These are summarized in Tables 4 to 6 and Figs 10, 11, 13, and 14. The above comparison highlights that there is a broad agreement between the key results obtained from case study implementation of the software prototype and those reported by Bowersox *et al.* [**1**]. Agreement of the results obtained from case study implementation of the software prototype with those reported in literature reflects validity of the model underlying the rule base of the software prototype.

8 CONCLUSION AND FUTURE RESEARCH

The intention of this research was to support decision makers in positioning decoupling points in supply chains. One way to achieve this is by providing tools with which they can visualize the consequences of their decisions from multiple perspectives. The feasibility of using knowledge-based technology to bring together view points of multiple domain experts and support decisions related to the positioning of decoupling points in supply chains has been demonstrated in this paper. The results obtained from the software prototype were compared with established literature and showed similar trends.

Major challenges in the use of knowledge-based technologies lie in the acquisition of knowledge from domain experts and the representation of knowledge in a suitable form. In this research, elicitation of knowledge from knowledge sources was carried out manually. As a result there were difficulties in separating domain knowledge from the domain experts' views or opinions. Once elicited, a separate issue lay in the representation of the elicited knowledge in an appropriate knowledge representation scheme. During the last few decades a number of knowledge acquisition software tools have emerged that may help improve the efficiency of the knowledge acquisition process. This research used production rules for the representation of knowledge acquired from domain experts. Representation of knowledge using production rules has a number of limitations. Three specific problems were experienced through the research reported in this paper. First, rules represent generality and so impose a lack of flexibility which, in turn, makes it difficult to represent exceptions to the general rules. Second, although rules are well suited for representing empirical information, such as associations between cause and effect, they are not adequate for other types of knowledge, such as descriptive knowledge. Finally, rules are implemented as independent entities but, as the size of the knowledge base grows, so interactions between rules become more likely and their impact difficult to predict. One approach may be the use of a combination of rules and frames for knowledge representation.

Areas for further development of the research lie in moving the focus on decoupling zones rather than points and in establishing mechanisms by which the models that underpin such systems might be validated. Evidence from recent seminars suggests a growing interest in ways of capturing and validating extracted knowledge through whole product lifecycles and associated networks of organizations.

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